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The Joint Milli-Arcsecond Pathfinder Survey: Introduction and Applications

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The United States Navy is developing the space-based Joint Milli-Arcsecond Pathfinder Survey mission (JMAPS) mission to support current and future needs for high accuracy star positions. The primary objective of the JMAPS mission is to generate a star catalog that is 15 times more accurate and 100 times denser than existing bright star catalogs. JMAPS will not only provide required star positions needed by high-accuracy, space-based orientation/attitude users, but JMAPS will also pathfind, mature, and risk-reduce technology for the next generation of high accuracy attitude determination systems. In addition, the JMAPS sensor, optimized to make very high precision measurements of star positions (astrometry), is ideally suited to improve position measurements of satellites and support formation flying applications. We will discuss the status of the JMAPS mission, including the current mission baseline, leading up to a CY 2013 launch.

Nomenclature

FPA	=	Focal Plane Assembly
JMAPS	=	Joint Milli-Arcsecond Pathfinder Survey
mas	=	milliarcsecond = 4.8 nanoradians
nm	=	nanometer
RSO	=	Resident Space Object

I. Introduction

Astrometry is the branch of astrophysics involving determination of the precise positions and motions of celestial objects on the plane of the sky. The basic astrometric parameters include position, parallax and proper motion. Astrometric position is measured in two celestial coordinates: right ascension (RA) and declination (Dec). Parallax is an apparent motion, directly related to the celestial object's distance. For distant objects such as stars, parallax is observed as a cyclic motion with a period of one year. Astrometric proper motion is related to a celestial object's real motion through space with respect to the Solar System barycenter. Photometry is the measure of the brightness of celestial objects, usually referenced to a specific spectral band, and is often provided by astrometric catalogs as key ancillary information.

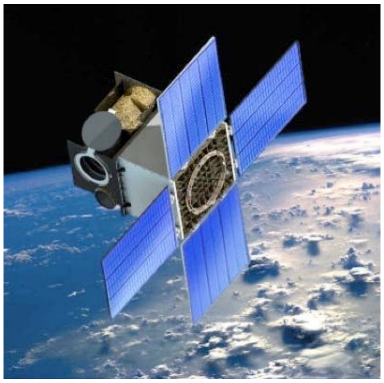

Figure 1. Artist's Concept of JMAPS in space.

Numerous catalogs are currently available describing the astrometric properties of a variety of celestial objects ranging in magnitude from the very brightest stars to the faintest quasars. Astrometric catalogs are also defined within specific wavelength ranges, such as visible, infrared, or radio wavelength regimes. The most accurate visible wavelength stellar astrometric catalog currently available is the Hipparcos catalog[1] based upon data obtained with the European Space Agency's Hipparcos space astrometry mission launched in August 1989. The at-epoch astrometric accuracy of the Hipparcos catalog is approximately 1 mas. Due to measurement uncertainties in the proper motions of the stars that make up the Hipparcos catalog, the astrometric accuracy of the Hipparcos catalog has been degrading by approximately 1 mas per year since 1991.

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JMAPS is a small, single-aperture astrometric spacecraft, funded by the U.S. government. The JMAPS mission is currently being developed by the U.S. Navy for launch in 2013. The principal objective of the JMAPS mission is to produce an all-sky visible and near IR astrometric and photometric catalog for 0^{th} through 14^{th} I-band magnitude stars with an accuracy objective of better than 1 mas in position, and photometry to the 1% accuracy level or better, for stars in the 1^{st} to 12^{th} magnitude range. The final JMAPS star catalog will be delivered in the 2016 timeframe. Astrometric positions will be reported in ICRS coordinates, tied to the ICRF though direct observations of the visible wavelength counterparts of radio wavelength ICRF sources. Combining Hipparcos measurements with JMAPS data will significantly reduce the temporal degradation in astrometric accuracy of the catalog; producing a combined catalog that will maintain high accuracy for decades. In addition, JMAPS will also pathfind technology for future space missions. An artist's concept of JMAPS in orbit is depicted in Figure 1.

II. JMAPS Overview

A. Spacecraft

The integrated JMAPS spacecraft concept is shown in Figure 2. JMAPS is a single-payload spacecraft consisting of a bus (bottom), with solar panels, and an instrument deck (top). The solar panels fold against the bus in a stowed and locked position during launch and are deployed on-orbit. In addition to housing the power subsystem, the spacecraft bus contains communications, thermal control, avionics, reaction wheel, and inertial measurement unit subsystems. The Attitude Determination and Control System (ADCS) is split between the bus and instrument deck. While the spacecraft is slewing, the star tracker, located on the instrument deck, determines spacecraft attitude to approximately 1 arcsecond. During standard observations the ADCS system holds spacecraft pointing stability to a 50 mas specification. This is accomplished by using the primary instrument to generate boresight pointing quaternions at a 5Hz rate as derived from observations of a handful of reference stars on the primary focal plane. The total mass of the spacecraft, including contingency, is approximately 180 kg and the spacecraft occupies a volume of 96.5 cm (h) x 71 cm x 61 cm.

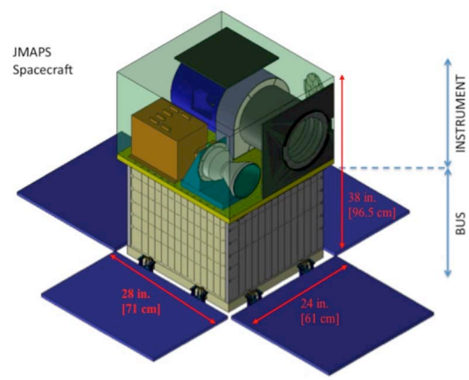

Figure 2. JMAPS spacecraft concept with solar panels deployed and labeled dimensions.

B. Instrument Overview

A depiction of the layout of the JMAPS instrument deck components is shown in Figure 3. The Optical Telescope Assembly (OTA) is the largest structure on the instrument deck, consisting of a single aperture, 19 cm diameter, f/20 telescope. The nominal point spread function (PSF) is 0.87 arcseconds full width half maximum (FWHM). The JMAPS field of view is 1.24 square degrees. The OTA supports a JMAPS astrometric bandpass of 700-900 nm; spectroscopic observations will be conduced within a wider 450-900 nm band. During normal observations, a sun shield (not shown in Fig. 3) will protect the OTA from direct exposure to solar heating. Tucked under the OTA (not seen in Fig. 3) is the Focal Plane Assembly (FPA). The JMAPS FPA consists of a 2 by 2 mosaic of Teledyne Imaging Sensor (TIS) H4RG-10 detectors, as shown in Figure 4. The H4RG-10 is a 10 micron pitch, 4192 by 4192 pixel CMOS-Hybrid detector. CMOS-Hybrid technology combines many of the best characteristics of CCD and CMOS technology. The nominal pixel subtense is 0.55 arcseconds, providing a sampling of approximately 1.6 pixels per PSF FWHM. USNO has sky-tested the first and second generations of H4RG-10 detector.[2] It is anticipated JMAPS flight devices will result from the third generation of the H4RG-10 detector. Major components of the instrument deck also shown in Fig. 3 are the Instrument Electronics Box (IEB), which houses the primary on-board electronics for both the instrument and bus, the Terma star tracker, and thermal

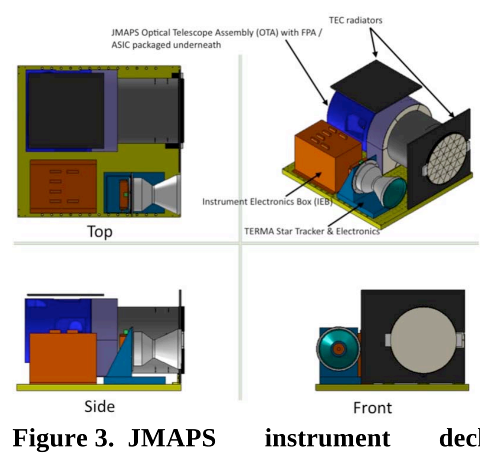

Figure 3. JMAPS instrument deck viewed from different perspectives.

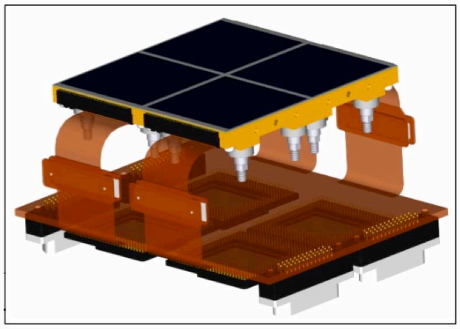

Figure 4. JMAPS 64 megapixel focal plane concept, consisting of a 2 by 2 array of TIS H4RG-10 CMOS-hybrid sensors.

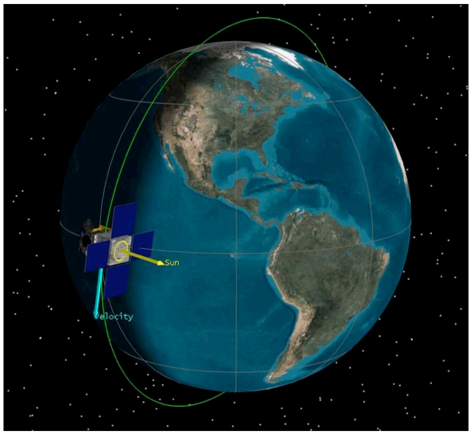

Figure 5. JMAPS in 900 km Sun synchronous terminator orbit.

radiators. Combined with a thermoelectric cooler (TEC), the radiators will help maintain the JMAPS FPA at a temperature of 193K, with a stability of 10mK.

C. JMAPS Operations Concept

JMAPS will be launched into a 900 km sun-synchronous terminator orbit (Figure 5) and operate in a step-stare mode, typically sweeping out swaths of the sky at approximately a 90 degree angle to the Earth-Sun line (regions of maximum parallax signal). JMAPS will operate in a step and stare mode, stepping from field to field, utilizing a four-fold field overlap pattern to ensure the rigidity of the resulting astrometric reference frame. Windowed FPA integration times of 1, 4.5 and 20 seconds will be used for the majority of stars. Shorter integration times (0.01 or 0.2 seconds) will be used for the brightest stars. Over the course of the JMAPS mission individual stars will be observed on the order of 40-60 times. In order to place the JMAPS astrometric reference frame on the International Celestial Reference System (ICRS), the optical counterparts of radio wavelength International Celestial Reference Frame (ICRF) quasars will be directly observed by JMAPS. Since most ICRF quasars are quite faint compared to the stars typically observed by JMAPS, integrations times as long as 500 seconds will be employed for the JMAPS observations of ICRF fields.

D. JMAPS Astrometric Accuracy

Analysis of the astrometric accuracy of the JMAPS mission indicates a single measurement astrometric precision of 5 mas will be achieved for the majority of stellar sources (see Figure 6). The "jagged" nature of the astrometric precision curves shown in Figure 6 is attributed to the differing integration times utilized for stars in particular magnitude ranges (see section II c, above). Through combination of multiple observations over the 2 to 3 year lifetime of the JMAPS mission an astrometric precision of better than 1 mas is obtained for the majority of stars in the JMAPS catalog.

Figure 6. (Left panel) JMAPS single measurement precision as a function of I-band magnitude. (Right panel) JMAPS mission precision as a function of I-band magnitude.

E. JMAPS Technology Development

JMAPS will incorporate a number of new technologies that will pathfind, mature, and reduce risk for a variety of new space missions. For example, the JMAPS optics, metering structure, FPA housing, and FPA packaging are constructed entirely of Silicon Carbide (SiC) (see Figure 7). The advantage of SiC over standard materials is in increased stiffness, and the minimization of both thermal gradients and of mismatches in the coefficients of thermal expansion of various optical components; all of which are critical for the high astrometric accuracy operation of the JMAPS instrument. The JMAPS focal plane employs a CMOS-hybrid active pixel sensor, offering improved immunity to on-orbit radiation damage and flexible read-out compared to CCD devices. JMAPS will employ low dispersion reflective gratings for stellar color sensing (slitless spectroscopy), and demonstrate 10 mas attitude sensing and 50 mas microsatellite pointing stability.

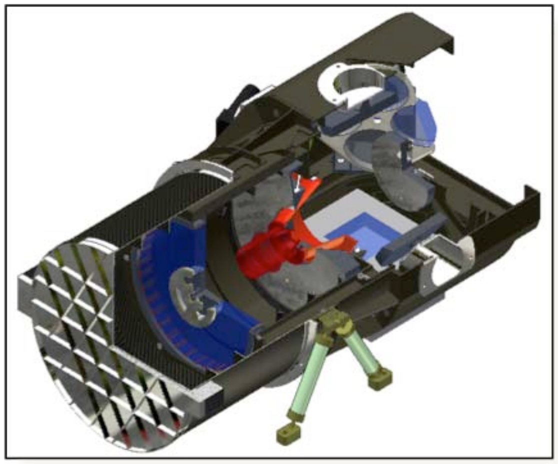

Figure 7. JMAPS OTA, with optical elements and metering structure fabricated from SiC.

III. JMAPS Applications

A. Space-based Orientation Determination

Specific high performance applications require individual orbiting satellites to be able to determine their space orientation (attitude or pointing) with very high accuracy. The most common and accurate method to determine space platform orientation is through utilization of high performance star trackers and high accuracy star catalogs. For example, Ball Aerospace and Technology Corporation developed the *Aspect Camera* for NASA's orbiting Chandra X-ray Observatory, and now markets the *High Accuracy Star Tracker* (HAST)[3], offering an orientation capability of order 100 mas. Current high accuracy star trackers typically utilize bright star astrometric catalogs, such as the Hipparcos catalog. However, given that a typical high performance star tracker allocates on the order of 10% of its orientation error budget to stellar astrometric positions, coupled with the continuing degradation in the accuracy of the Hipparcos catalog (see section 1, above) suggests that the accuracy of the currently available star catalogs is the principal limiting factor for improvements in star tracker orientation performance.

The impact of the JMAPS program on the improvement of the space-based orientation infrastructure is two-fold. First, the JMAPS program will update the astrometric accuracy of the bright stars typically utilized by high performance star trackers, not only mitigating stellar position as an error source for current high performance star trackers, but also removing stellar position error as an impediment to improving the performance and developing a new generation of higher accuracy star trackers. With JMAPS observations combined with those made by the Hipparcos satellite, the resulting astrometric catalog will provide mas-level astrometric accuracies for decades. Secondly, JMAPS pathfinds and matures a number of technologies relevant to the commercial development of the next generation of star trackers (see section IIe, above). In addition, JMAPS will provide a key on-orbit space-based demonstration of 10 mas orientation determination, utilizing a small telescope not much larger than a typical high performance star tracker.

B. Satellite Position Measurement and Formation Flying

The JMAPS mission will have a two-fold impact in the area of satellite (Resident Space Object = RSO) position measurement. Observations contributing to RSO position determination are typically made by ground or space-based sensors that measure plane-of-the-sky angular separations between a particular RSO and background field stars. JMAPS will contribute to the improvement of RSO position determination by providing more accurate positions for the background reference stars, through 14th magnitude. Indeed, for an RSO in a geo-orbit the mas-level JMAPS star catalog provides a stellar reference grid with a linear precision of 20 cm.

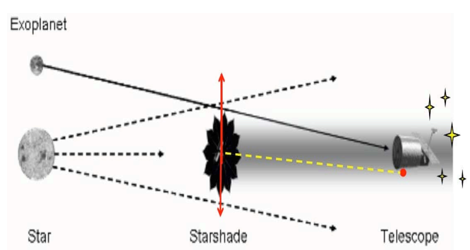

Figure 8. The NWO alignment problem: A JMAPS-like sensor is utilized to align a starshade and telescope at the few meter level, allowing a detailed study of the much fainter exoplanetary system (From Dorland and Dudik, 2009).

In addition, many existing and planned ground and space-based sensors utilized for RSO orbit determination are optimized for wide field-of view search capability, with only a moderate capability for obtaining accurate positional metrics. On the other hand, the JMAPS instrument is designed and optimized to obtain high accuracy stellar position measurements. As an instrument optimized to measure stellar positions, when combined with a high accuracy stellar catalog, JMAPS will be capable of making the high metric accuracy measurements of the plane-of-sky positions of RSOs, with unprecedented accuracy. It is also important to note that as a space based instrument in a LEO orbit, the JMAPS orbit will provide a trigonometric parallactic baseline for improving RSO position measurement; observations separated by 55 minutes (one half a JMAPS orbit) are also separated by approximately 14,000 km.

Finally, the astrometric capabilities of the JMAPS sensor will positively impact high accuracy, long-distance, formation-flying applications. Dorland and Dudik[4] studied the performance of a JMAPS sensor with regards to satellite formation flying for the New World's Observer (NWO) mission. The NWO is a proposed exoplanet characterization mission utilizing a star shade to block the light from an exosolar planetary system's primary star, facilitating study of the extended planetary system (see Figure 8). The Dorland and Dudik study suggests that utilizing a moderately powered beacon attached to the primary NWO telescope and a JMAPS-class sensor on the starshade allows alignment at the few meter level at distances of 50,000 km or more.

IV. Conclusion

JMAPS is an astrometric star mapping mission, currently under development by the U.S. Navy for launch in the 2013 timeframe. The primary goal of the JMAPS mission is to support current and future needs for high accuracy star positions. JMAPS will also support the development of key technologies that will reduce risk for future space missions, while supporting secondary applications such as RSO position determination and precision long distance satellite formation flying.

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